Detectors for Infrared Science

Working group report: G.L. Carr, J. Scott, G.P. Williams

1. Scientific motivation

The exceptional qualities of infrared synchrotron radiation have opened new research frontiers in a variety of scientific disciplines[1]. Mid-infrared microspectroscopy is now capable of sensing chemical features within individual living cells[2], and is being developed as a probe of chemical changes associated with disease[3]. The properties of nanometer-sized particles from the Solar System are being compared with their distant stellar cousins[4]. Complex, heterogeneous soils are probed for environmental contaminants[5] and the chemistry of corrosion is probed in the microscopic pits where the process begins[6]. Despite these successes, the quantity of interest is often near the sensitivity limit for existing instrumentation. For example, proteins can be readily identified from the Amide I vibrational absorption in the 6 micron wavelength range, and regions high in protein content can be located within some cells. This absorption feature is usually a mixture of several individual vibrational modes whose position and strength vary with structure[7]. As a result, when signal-to-noise (S/N) is sufficiently high, these absorption features can be deconvolved into individual modes that can identify and characterize proteins through their structure. Achieving the necessary S/N in a microscopic region is possible, but can require excessively long sampling times. An order of magnitude improvement in S/N would allow many more regions to be sampled and mapped for protein content. Similar improvements in S/N will benefit all the scientific investigations described above, enhancing the detection threshold for locating and identifying contaminants in environmental systems and allowing smaller particles to be investigated and analyzed. With the demonstration of vibrational spectroscopy on individual interplanetary particles less than 100 nm in size[4], we anticipate the application of synchrotron-based infrared microspectroscopy to the study of nanoparticles and other nanostructures. Here again, the ability to extract absorption signals from such small specimens will depend critically on the S/N.

2. Infrared detectors: existing technology

2.1 Introduction

An infrared detector system consists of four major components: 1) an infrared sensitive element or mechanism (anything which converts the presence of infrared into an electrical signal), 2) an optical system for bringing light to the element and controlling both the spectral range and the field of view (FOV), 3) read-out electronics and 4) a container for reducing ambient fluctuations and often to provide cryogenic operating temperatures. Each of these component systems is designed and optimized to deliver the best performance for a given application. It is helpful to define some figures of merit for comparing detector performance and setting performance goals. One of these is the Noise Equivalent Power, or NEP, defined as the incident power level for which a detector yields a signal-to-noise ratio of unity for a given response bandwidth. Typical values are in the range of 10^{-12} W/(Hz)$^{1/2}$. The inverse of this quantity is referred to as the detectivity, D.

2.2 Noise and "BLIP"

In contrast to higher energy (shorter wavelength) spectral ranges, the performance of an infrared detector is strongly affected by the 300K ambient conditions of most measurements. In particular, the peak of the blackbody spectrum for a 300K source occurs in the mid-infrared, near a wavelength of 10 _m (or a frequency of 1000 cm $^{-1}$, measured in units of wavenumbers _ 1/_ with _ in cm).The intrinsic fluctuations of background radiation represent a fundamental limit on the performance of an infrared detector, and the goal of most detector designs is to minimize the amount of background radiation reaching the detector while at the same time keeping all other sources of noise at an even lower level. Such a detector is said to have achieved its ideal, background-limited infrared photodetection (or BLIP) and this detectivity limit is usually referred to as D_{BLIP}. Note that D_{BLIP} depends on the detector's active area, FOV and spectral range. Other sources of noise stem from electrical fluctuations in the detector element and the amplifier electronics.

2.3 Conventional spectroscopy applications

We are fortunate that both commercial and military applications have motivated significant developments in infrared sensor technology, and high quality detector systems (often achieving BLIP) are available for most infrared wavelengths. The detector systems commonly used for infrared spectroscopy applications include InSb photodiodes (frequencies above 2000 cm^{-1}), MCT (700 cm^{-1} to 4000 cm^{-1}) extrinsic Ge or Si photoconductors (330 cm^{-1}to 2000 cm^{-1}), and the Si composite bolometer (below 1000 cm^{-1}). An example of such an IR detector design is found in the standard detector for mid-infrared spectroscopy; the _N_2 cooled $Hg_{1-x}Cd_xTe$ (MCT) photoconductor. MCT is a narrow gap semiconductor alloy with a long wavelength cutoff (band gap energy) that varies with composition. Cooling the detector and an aperture-defining shroud to 77K reduces the thermal background radiation and also improves the electrical noise qualities of the element. A typical system has an MCT element 1 or 2 mm in size and a 60 degree FOV (determined by the cooled shroud). A special low noise preamplifier completes the system, which can easily achieve

BLIP. Note that the amount of background radiation received by the detector depends on the element's size and the FOV. Decreasing either (or both) will reduce the background level and allow for higher performance. For example, an MCT detector system intended for microspectroscopy applications has an element 0.25 to 0.1 mm in size, yielding a ~ 10-fold reduction in the noise signal from background radiation (for the same FOV). But such a reduction will not translate into a similar performance benefit if another source of noise becomes predominant. In this case, improved detector materials and/or electronics are necessary.

3. Infrared synchrotron radiation: beamlines and instrumentation

3.1 Diffraction limited brightness

Though the synchrotron source possesses a number of interesting and unique qualities that enable particular measurement techniques, most of the usage exploits the high source brightness for microscopy and similar throughput-limited techniques. Of course, the high brightness synchrotron source extends IR spectroscopy into regimes not feasible with conventional sources. The power from a synchrotron source is similar to that from a thermal source a few millimeters in diameter. But in contrast to the thermal source, the synchrotron source is diffraction-limited in size. An optical system with a diffraction-limited throughput may use less than 1% of the light from a conventional thermal source, whereas the synchrotron source is optimally matched. The problems being pursued by infrared microspectroscopy with synchrotron radiation are already at the diffraction-limit, and other measurements (such as ellipsometry) can easily reach the diffraction-limit for even modest size specimens.

In contrast to VUV and X-ray methods, the lower emittance of new synchrotron radiation sources has not benefited infrared spectroscopy where even 2^{nd} generation sources achieve diffraction-limited brightness. Increasing the stored beam current will increase the detected signal, but most synchrotron radiation facilities are already at, or near to, their operational limits.

3.2 Potential as a line source

A conventional infrared beamline collects a horizontal angle of a few degrees (several 10s of milliradians), presenting a diffraction-limited point source for wavelengths beyond about 10 microns. Only for significantly shorter wavelengths (< 2 microns) is the horizontal extent of the electron beam arc resolved and the source becomes extended in this direction. In theory, a beamline could be developed to collect a much larger horizontal angle and provide an extended line source. A linear array detector then would be useful for exploiting such a source.

3.3 Rapid scan FTIR and detectors

Mid-infrared spectroscopy is almost always performed using rapid-scan interferometers due their excellent efficiency and compatibility with microscopes and other optical accessories. The measured interferogram intensity is Fourier Transformed to produce the InfraRed spectral intensity, giving this FTIR method its name. These FTIR instruments are highly refined and span readily span most of IR spectral range.

Detectors intended for use with synchrotron radiation must be compatible with rapid scan FTIR instruments. In general, the detectors supplied with commercial spectrometers are not likely to be optimized for use with such a diffraction-limited source. This suggests one strategy for improving the performance of existing detector systems. Though the source and optical instrument can be optimally matched, it is unlikely that the IR detector is optimized too. This is because most of the IR detectors at synchrotron facilities are part of commercial spectrometer systems designed to accept light from a conventional source several millimeters in size.

3.4 Other techniques

Other areas of detector improvement are desirable, but pertain to less commonly used techniques. These include coherent detectors for the very far IR and fast detectors to work with the short duration pulses from the synchrotron storage ring. Detectors for such applications deserve attention, but the requirements tend to be quite specialized and better left to the research groups pursuing these methods.

4. Opportunities for improvements

Here we identify areas where detector improvements are expected to have a significant impact on synchrotron-based IR spectroscopy. We focus on one category of improvement that can immediately benefit existing facilities. The other areas are dependent on modifications to either the beamline optical system or the spectrometer instrumentation.

4.1 Detector systems for diffraction-limited performance

For situations where the 300K fluctuations limit the S/N, reducing the amount of background radiation falling on the detector is necessary for improving performance. There are three approaches to reducing this noise contribution: 1) reduce the field-of-view (FOV) or solid angle _, 2) reduce the detector's area A, and 3) limit the spectral range to avoid regions where the background photon flux is greatest.

In contrast to conventional thermal IR sources, synchrotron infrared radiation provides a diffraction-limited point source. Assuming an ideal, properly matched optical system, the spotsize at the detector for a diffraction-limited experiment will be 1.22_/NA whereNA=sin_ is the numerical aperture of the detector optics. The NA for a 60 degree FOV is 0.5, so a 0.25 mm detector intended for microspectroscopy is more than 15 times the diffraction-limited spotsize for a wavelength of 6 microns (a typical mid-infrared wavelength). A smaller detector or FOV will reduce the background noise considerably. This leads us to define a new measure of performance (which we will call DBLIP) as BLIP for diffraction-limited acceptance. Since the diffraction limit varies with wavelength, designing a detector for achieving DBLIP over any significant spectral range brings additional challenges.

The potential for improvement depends on the wavelength range of interest. Different types of detectors are employed for the far-infrared compared to the mid-IR, and different methods for improving their performance for diffraction-limited conditions are expected. Even a detector optimized for background-limited performance in one spectral range will fall seriously short of this limit in other parts of the spectrum.

4.2 Small area arrays

Developments in large area detector arrays are not expected to immediately benefit synchrotron infrared research, since optimal infrared beamline’s provide a nearly diffraction-limited “point-source”. But there may be uses for small area arrays, especially those that can be “read out” at rates compatible with rapid scan FTIR spectrometers. For beamlines where the horizontal collection significantly exceeds the diffraction-limit, a spectrometer system employing a linear array may prove useful for imaging. Such parallel data collection would yield a significant benefit for microspectroscopy imaging applications. Spectrometry instrumentation and electronic readouts would also need to be developed.

4.3 Speed

Since the output of all synchrotron storage rings is pulsed, detectors capable of working with these pulses are useful. Systems capable of detecting across wide spectral ranges are useful for synchronizing two sources, or selecting particular pulses from a pulse train. In other cases they me be used for sensing particular time segments of a sample’s response to avoid the effects of thermal diffusion. Each of these cases tends to be specialized and therefore best managed by the particular research groups pursuing these techniques.

4.4 Coherent

Advanced concepts for producing synchrotron radiation are often based on short bunches such as those produced by LINACs. Similar to the coherent THz pulses produced by laser techniques, the acceleration of short electron bunches will produce considerable coherent radiation at long wavelengths. Systems capable of coherent detection may become important not only for the characterization of very short electron bunches, but also as part of spectroscopy systems utilizing the coherent radiation.

5. Recommendations

5.1 Single-element DBLIP Detectors

5.1.1 Far infrared.

We believe that existing _He cooledbolometer technology is sufficient for achieving diffraction-limited performance, and effort should focus on the optical system for limiting the background in a convenient and optimal manner. We recommend a brief study to confirm this and also to design a optical package (e.g., cooled filters and apertures) for installing into existing far-infrared bolometers from vendors such as Infrared Laboratories (Tucson, AZ).

5.1.2 Mid-infrared

The diversity of measurement issues and detector technologies makes it difficult to identify the optimal direction to pursue without conducting a detailed study/analysis. Such a study must address the particular spectral ranges deemed most critical and which detector technologies are most likely to succeed in meeting the demands of diffraction-limited detection. Individual detectors are likely to meet this performance level over modest spectral ranges, but achieving this over a broader spectral range is a substantial challenge. It is likely that a set of IR detectors will be needed (similar to the present situation for conventional IR spectroscopy), each optimized for a particular spectral range. Detector materials include extrinsic Si:B (4.2K), $Hg_{1-x}Cd_xTe$ (MCT, 77K) and InSb (77K). But it is not known whether MCT achieves diffraction-limited performance for the alloy compositions needed to properly span the spectral range between Si:B and InSb. This must be part of an analysis program.

5.2 Arrays

The development of linear array detector systems should only occur in concert with beamlines to produce an extended source. We are not presently aware of any existing or proposed beamline that would offer such a source.

5.3 Fast detectors

Small number of groups and diverse needs suggests this activity is best pursued by those groups to solve particular / specialized problems.

5.4 Coherent

Used at one or two SR facilties as diagnostic for short electron bunches. No need for the synchrotron infrared beamline and User at this point (future).

6. Summary

Improvements in IR detectors for synchrotron radiation research should provide needed increases in sensitivity and boost scientific productivity. A decade improvement in S/N is desirable, but even factors of 2 or 3 will be quite beneficial. The costs for such improvements are expected to be small in contrast to the facility investment. A complement of infrared detectors, optimized for diffraction-limited performance, should be developed for use at infrared synchrotron radiation facilities. The particular performance goals will require more feedback from the User community.

The application of more specialized detector concepts (e.g., arrays) dependson significant changes to beamline design and their construction. Future IR beamlines that extract a larger horizontal angle would be candidates for developing linear arrays use in IR mapping/imaging.

References:

[1] See, for example, G.L. Carr et al and other articles in Infrared Synchrotron Radiation, In Nuovo Cimento, P. Calvani and P. Roy, eds.

[2] N. Jamin et al, Proc. Nat'l Acad. Sciences

[3] micro and disease ref. IUMAS?

[4] J.P. Bradley et al, Nature

[5] U. Ghosh et al

[6] G. Halada et al

[7] Amide I deconvolution

[8]

[9]

[10]. For a fixed FOV, the noise power due to background radiation as well as internal sources of electrical noise usually scale with the detector's area. For this reason it is convenient to define D* which is the detectivity normalized to the square root of the detector's effective area.